Root Growth, Calcite Precipitation, and Gas and Water Movement in Fractures and Macropores: A Review with Field Observations[1]

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ABSTRACT. **Recent research on the presence and dynamic nature of fractures and soil macropores has generated interest in their impact on root growth in minimally disturbed soils due to no-till or reduced tillage farming practices. The balance of water, air, and nutrients in the subsurface is, in part, determined by the structure and type of macropores. Biological systems can create and expand the network of biopores, or change the biogeochemistry within a given fracture or biopore. In the field, roots have been observed to grow preferentially through fractures. At a demonstration test pit at The Ohio State University (OSU) Molly Caren Agricultural Research Center in London, OH, networks of roots were exposed within fractures at 1.0 to 2.0 m in depth. A streambank on the OSU Waterman Agricultural and Natural Resources Laboratory in Columbus, OH, provided a natural exposure of fractures and roots preferentially growing in these fractures at depths of 1.0 to 1.5 m. A deeply incised streamcut in Batavia, OH, revealed live roots growing (at a depth of 15 to 20 m) within pre-Illinoian glacial till fractures. Microbial action upon living roots and in the degradation of dead root material can lead to calcite precipitation and infilling of fractures and other macropores. Earthworm burrowing can redistribute nutrients to the deeper subsurface, facilitating root growth at greater depths. During construction of the small test pit located near Tremont City, OH, a live earthworm was observed within a fracture at a depth of approximately 3.0 m.**

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INTRODUCTION

The growth of the aerial portion of a plant is dependent on an actively growing root system. Soil porosity is an important factor affecting the growth and development of that root system. Pore space influences root penetration, provides for the movement and storage of water and air through the soil, and affects the nutrient status of the soil (Glinski and Lipiec 1990; Jensen and others 1998). Soil pores are divided into classes based on diameter at the narrowest point. The major categories are macropores >100 µm, mesopores 30-100 µm, and micropores <30 µm (Glinski and Lipiec 1990). Fractures and channels fall mainly into the macropore category. Macropores may be divided into two main types: natural fractures and cylindrical biopores (Cornish 1993; Hirth and others 1997; Hoff and others 1998; Jensen and others 1998). Fractures can be contractional (that is, created by desiccation or freezing/thawing) or geologically formed such as tectonic fractures or natural faults (Klint and Gravesen 1998). Cylindrical biopores are those created by tunneling insects and small animals, earthworms, or decaying roots. Other macropores may be formed by subsurface erosion channels.

Roots require air, water, and nutrients to grow. Except for some specially adapted aquatic and wetland plant species, the oxygen needed for root respiration comes from the air in pore spaces. An improper balance of air and water in soil will limit root growth. Glinski and Lipiec (1990) state that it is not so much porosity that determines availability and transportation of soil solutes and soil air, but pore size distribution. Their research indicates that it is the quantity of pores between 0.2 and 60 µm that is the major factor that determines the reserves of water availability to a plant. These pores hold water against the force of gravity through capillarity. Larger pores lose water to gravity, and water held in smaller micropores is inaccessible to roots. To allow a balance of air and water and to prevent anoxic conditions around roots, sufficient macropore space is needed to allow excess water to drain after rainfall or irrigation, although the ideal balance of micropore to macropores is unknown (Luxmoore 1981).

In addition to drainage, macropores (fractures and large biopores) also provide a means for roots to penetrate the otherwise impenetrable layer of soil that often occurs below tilled soils as a result of vehicular compaction and other factors (Glinski and Lipiec 1990). The burrows of earthworms contain fecal matter (casts) left behind by the worms. These casts provide nutrients for plant growth (Hirth and others 1997). The decayed organic material left behind in old root channels may also provide nutrients for new roots penetrating those channels. Likewise, the decaying organic material may be used by soil bacteria and fungi, leading to calcite precipitates filling the old root channels.

Many of Ohio's glacially-derived soils have fractures (Tornes and others 2000). Fractures and soil biopores can provide a beneficial environment for biological systems to flourish in the subsurface. In turn, biological entities can create and expand the network of biopores, or change the biogeochemistry within a given fracture or biopore. The synergistic interaction between the physical macropore system and its associated biological system is examined in this report, which includes an extensive literature review of the most recent findings and presents some field observations from four Ohio sites.

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MATERIALS AND METHODS

This paper presents a review of fractures and biological systems, especially plant roots and microbial systems, and the compilation of unpublished records of root development within fractures at the demonstration test pit at The Ohio State University (OSU) Molly Caren Agricultural Research Center in London, OH, and at streamcuts on the OSU Waterman Agricultural and Natural Resources Laboratory in Columbus, OH, and Batavia, OH. In addition, deep earthworm burrows are described from a test pit site near Tremont City, OH. Methods include literature review and direct observation at the four field sites.

REVIEW OF LITERATURE

Distribution and Genesis of Different Macropore Types

The distribution and type of macropores depends on soil type, climatic factors, and agricultural management practices. Fractures are common in Ohio's unconsolidated subsurface materials, including glacial tills and glaciolacustrine or lake plain sediments (White 1982). These features can extend from the soil structural units into the lower geologic strata, acting as conduits for ground water and contaminant flow from shallow to deep systems (Kirkaldie 1988; Kirkaldie and Talbot 1992). Tectonic fractures and faults were formed during glacial loading and unloading and tectonic activity in some regions. The density and orientation of the fractures and faults that result depend on the age and type of geologic process that formed them. Older glacial deposits such as Illinoian tills often have greater fracturing and greater leaching of soluble minerals from the matrix than younger deposits such as Wisconsinan tills. Lodgement tills typically have more shear stress fracture networks. Ablation tills or glaciolacustrine tills typically exhibit more polygonal fracture networks due to historic desiccation processes. These fractures and faults can intersect the layers within the soil profile and create a hydraulic connection between the different types of macropores. This is an important aspect for drainage.

In clayey till soils, root holes have been documented to be widespread in the upper till, but at lower depths the roots seem to concentrate within the major, preexisting fractures (Klint and Gravesen 1998). In the same soils, contractional fractures resulting from desiccation and freeze-thaw cycling were observed in the upper bioturbated till. Further down, older fractures of different origin were reactivated during extremely dry periods (Klint and Gravesen 1998).

Earthworm burrows are reported to be extensive in the uppermost 1.5 m of a clayey glacial till soil. Here more than 400 earthworm burrows per m^2 have been found; most of these were primarily vertical in orientation. The number decreased abruptly below 1.3 to 1.5 m below ground surface (Klint and Graveson 1998). However, the number of earthworm burrows can vary with tillage practices, seasonal and annual climatic conditions, and earthworm species present. In northeast Ohio soils, earthworm populations were larger in no-till fields compared to tilled fields, presumably as a result of less disturbance (Bohlen and others 1995). Biomass of some earthworm species decreased during droughts, but the biomass of those species capable of digging deep burrows and either aestivating in them or remaining active and returning to the surface at night to feed did not decline. Bohlen and others (1995) suggested that introducing a deep burrowing species that remains active, for example, *Lumbricus terrestris*, could lead to significant hydrologic changes in the area. They also suggested that in areas where no-till was followed by several years of grassland, the increase in worm populations was more the result of grassland than no-till. Similarly, Springett and Gray (1997) showed that earthworm populations were greater in undisturbed pastures versus pastures that had been cut or mown.

Macropores and Root Growth

Roots extend by division and subsequent elongation of cells just behind the tip of the root. The tip itself is a layer of thickened, tough cells called the root cap. The dividing, elongating cells literally push the root through the soil. In moist and/or soft soils, roots grow by deforming the soil matrix. However, in dry or hard soils such as glacial till-derived soils, roots often follow the path of least resistance created by macropores (Logsdon and Linden 1992; Klint and Gravesen 1998). At a field site near Sarnia, Ontario, root casts were observed in glacial till fractures to depths of 3.0 to 4.0 m (Ruland and others 1991).

When tillage practices result in a noncontinuous system of channels and pores through the soil, root growth is influenced. A similar situation occurs in the construction and maintenance of sports fields. A loose layer of tilled or prepared soil directly on top of a more compact, untilled layer can result in root growth becoming concentrated in the soft layer (Lipiec and others 1993). The concentration of roots in a relatively narrow region of soil can adversely affect topgrowth, especially when water and nutrients become depleted in the soft region. Although the adverse effects can be overcome with irrigation and fertilization, these practices are expensive and add significantly to the cost of crop production or turfgrass maintenance.

Macropores and Gas Exchange

The metabolic processes for adequate root growth depend on the availability of sufficient oxygen to sustain respiration. Although most plants can withstand short-term oxygen deprivation, optimal growth depends on a constant and consistent supply of oxygen to the root. In general, the critical oxygen level in soil for plants begins in the range of 5 to 10% by volume (Glinski and Lipiec 1990). Soil oxygen decreases with depth. When macropores form a continuum into the soil profile, oxygen diffusion occurs into the soil matrix as indicated by a higher oxygen diffusion rate (Glinski and Lipiec 1990). Under such conditions, root respiration and consequently root growth can occur at greater depths.

In addition to supplying oxygen to deep roots, macropores also provide for stable oxygen concentrations at all depths (Glinski and Lipeic 1990). Anoxic conditions resulting from waterlogging of soils can result in damage or death of the roots. Macropores also help insure rapid drainage of water after heavy rainfalls. In circumstances where oxygen levels are low, the concentrations of other gases may be relatively higher. These gases (for example, ethylene, methane) may be harmful to root growth and development (Glinski and Lipiec 1990). Besides being an atmospheric gas, ethylene is a hormone produced by plants that causes senescence and death of plant cells. When produced and regulated by normal plant metabolic activity, ethylene serves a role in the natural development of plants. When exposed to exogenous ethylene, or when ethylene is produced by an environmental stress such as waterlogging, plant cells can prematurely senesce and die.

Water Flow and Nutrient Transport via Macropores and Earthworm Burrows

Macropores are important conduits for both the lateral and vertical flow of water through soil. In a series of laboratory studies on 30 × 30 × 30 cm undisturbed soil blocks, it was found that water flow through the blocks was dominated by a few macropores (Shipitalo and others 1990; Shipitalo and Edwards 1996). This was the case under widely varied antecedent moisture conditions, although it was observed that increasing soil water content did increase the flow of water through the matrix. Nonetheless, flow was most often associated with one or more macropores, and the largest flows were attributable to earthworm burrows over 5 mm in diameter. Whether or not the burrow was occupied by a live earthworm did not affect the ability of the macropore to conduct water, in fact for three of the blocks, the greatest flow volumes were produced from zones containing occupied earthworm burrows (Shipitalo and Edwards 1996).

As a result of the channeling of water, macropores also influence the distribution and availability of soluble nutrients through the soil matrix. Most plant nutrients are cations. The cation exchange capacity of soils is an important factor in soil fertility (Marschner 1986). Soil nutrients tend to be most available in the upper strata of the soil profile, mainly because of the decay of organic material. In cultivated fields, the application of fertilizer also increases the available cations in the upper strata. Cation capturing by soil particles limits the movement of these nutrients to deeper levels. For roots to grow at deeper strata where essential nutrients are often limited or present in an unavailable form, these nutrients may be carried to the deeper regions by water flowing through hydraulically active macropores (Hoff and others 1998). The type of pore influences how elements move through the soil profile. Jensen and others (1998) showed that phosphate (an essential plant nutrient), generally considered to be unleachable, can be leached through macropores. However, the efficacy of the pores to transport phosphates was shown to depend on the lining of the pores. Those pores with a lining that did not absorb phosphate were more efficient than pores whose lining contained phosphate absorbers. Earthworm burrows were the most effective conductors of phosphate through the soil.

Earthworm burrows may also influence nutrient supply to plant roots due to the earthworm castings (feces) contained within the burrows. Earthworm castings often have higher concentrations of nutrients than surrounding soil, especially soils in lower strata. However, Hirth and others (1997) found that roots did not elongate preferentially toward earthworm burrows compared to other macropores, whereas Springett and Syers (1979) reported that roots did elongate preferentially to earthworm casts. In the latter experiments, the roots had been allowed to grow for a longer period of time than in the former experiment. Also it appears that Hirth was comparing macropores to earthworm burrows while Springett and others investigated only casts. Although the earthworm burrows may not be beneficial themselves as sites of preferential root growth, the redistribution of nutrients from the surface via casts likely does benefit root growth. As the casts are degraded by soil micro-organisms, nutrients can be gradually absorbed into the surrounding soil and become available to roots.

Microbially Mediated Calcite Macropore Linings

The transport of air, water, and nutrients through fractures and other macropores not only enhances root growth, but also microbial activity leading to the formation of linings in the pores, and in many cases calcite infilling. White or greyish white, friable calcite materials were observed on fracture faces (Fig. 1) at the large geologic test pit excavated at London, OH, and along fracture traces (Fig. 2) at a streambank in Columbus, OH. Similar powdery calcite coatings on the walls of fractures have been described (Newman and others 1997; Klint and Gravesen 1998) and chemically analyzed (Boquet and others 1973; Graustein and others 1977; Klappa 1979; Fausey and others 2000). Partially decomposed root material was also noted in some of these calcium filled features. Newman and others (1997) proposed a model for the biogeochemical transformations that take place within pores leading to the production of linings made of calcite or mixed calcite and clay. The progression of a fracture from empty to calcite coated or calcite filled can be described as follows:

1. The vertical fracture is formed via contractional, geologic, or biological mechanisms.
2. Roots grow into and fill the fracture.
3. Mycorrhizal fungi grow in conjunction with the plant roots.
4. Eventually the root dies due to normal turnover, erosion, or other means.
5. Aerobic fungi and bacteria decompose the dead roots.
6. Fungal fibers become calcified (Klappa 1979) and/or calcium oxalate crystals grow on fungal hyphae as a metabolic byproduct (Graustein and others 1977).
7. Certain aerobic soil bacteria decompose calcium oxalate and cause direct precipitation of calcite (Boquet and others 1973).

FIGURE 1. Root network within greyish-white subsurface fracture face at a test pit on The Ohio State University (OSU) Molly Caren Agricultural Research Center in London, OH.

8. If the fracture becomes anaerobic or the nutrients are completely consumed, the fungi will die and anaerobic bacteria will decompose the remains, including the calcified fungal fibers.

Calcite deposits and infilling can also be the result of non-biological processes such as changes in pH, temperature, or salinity. However, Boquet and others (1973) reported that microbially mediated calcite formation was a common occurrence and postulated that under suitable conditions, most bacteria are capable of forming calcite crystals. Regardless of the source, calcite and/or calcium oxalate infilling causes changes in pore structure and pore dynamics. These changes affect the ecosystem by providing a reactive reservoir of calcium and pH buffering capacity and, by chelating iron and aluminum, the calcium oxalate allows phosphorus and potassium to remain available for plant roots (Graustein and others 1977).

FIGURE 2. Root hairs within greyish-white fracture at a streambank on the OSU Waterman Agricultural and Natural Resources Laboratory in Columbus, OH.

RESULTS AND DISCUSSION OF FIELD OBSERVATIONS

Observations of Preferential Root Growth in Fractures

Roots were observed growing within fractured tills at three Ohio sites: the soils/geologic test pit at The Ohio State University (OSU) Molly Caren Agricultural Research Center in London, a streambank on the OSU Waterman Agricultural and Natural Resources Laboratory in Columbus, and a streamcut in Batavia. At the London site, roots were exposed at 1.0 to 2.0 m below ground during excavation of the pit described by Christy and others (2000). A dense network of roots had grown preferentially along the calcite-coated iron-poor planar surfaces of the fracture faces (Fig. 1). The matrix material between fractures was of low permeability, whereas the more permeable fractures allowed root penetration far beyond what would be expected in unfractured parent material alone. Hydraulic conductivities were measured in the field at the London site; for boreholes intersecting fractures the hydraulic conductivity was 1.25×10^{-5} cm/sec (0.018 in/hr) which was one order of magnitude greater than for boreholes located in the till matrix (Fausey and others 2000).

At the Columbus site, the fractures were naturally exposed through the gradual erosion of the streambed by flowing water. The height of the streambank varied from 1.0 to 1.5 m above the stream's water elevation. The fractures, stained greyish-white from calcite deposition and iron leaching, stood out from the brown silty clay loam Kokomo soil. Thin root hairs were observed preferentially growing within the fracture affected zones (Fig. 2).

A deeply incised streamcut in Batavia, OH, located on Backbone Creek, a tributary to the Little Miami River, was examined for glacial stratigraphy and fractures. This Clermont County streamcut, which is 50 m wide and as much as 20 m high, exposed modern soil horizons formed in Wisconsinan loess overlying Illinoian till, and a thick paleosol formed in pre-Illinoian till (Teller 1970). The base of the deepest exposed layer, the pre-Illinoian till, was at creek level overlying Ordovician limestone bedrock, which was observed near the west end of the cut. Fractures were evident in all layers, often traversing two or more stratigraphic layers with a single fracture trace. Upon carefully cleaning the fractures using archaeological techniques, live tree roots were discovered to have preferentially grown through these fractures (Fig 3). This photograph was taken of the deep paleosol in the pre-Illinoian till layer. The roots were 15 to 20 m below the surface vegetation supporting this root growth.

Observations of Preferential Earthworm Burrow Penetration in Fractures

During construction of the small test pit located near Tremont City, OH, as described by Christy and others (2000), a live earthworm was unearthed at a depth of approximately 3.0 m. The site was in northern Clark County and was in a Miamian soil. The earthworm was observed coming out of a vertical fracture that had been

FIGURE 3. Roots within pre-Illinoian till paleosol fracture at a stream-cut on Backbone Creek, a tributary to the Little Miami River in Batavia, OH.

widened in the burrowing process. A trail of castings was left behind as the earthworm exited the exposed fracture. As was the case with the observations of preferential root penetration, the matrix material between fractures at this site is of low permeability, whereas the more permeable fractures allow earthworm burrow penetration beyond what would be expected in unfractured parent material.

CONCLUSIONS

Macropores—whether of geological, climatic, or biological origin—influence the growth of vegetation. The balance of water, air, and soil nutrients is in part determined by the structure and type of soil macropores. Roots have been shown to grow preferentially through fractures and other macropores. Earthworm burrowing can redistribute nutrients to the deeper subsurface, facilitating root growth at depth. Microbial action upon living roots and in the degradation of dead root material can lead to calcite precipitation and infilling of fractures and other macropores. Future research needs include determining how long-term (20+ years) no-tillage farming practices affects soil pore characteristics in different types of soils and if certain deep burrowing earthworm species can be successfully used to improve soil characteristics in areas where root and plant growth has become inhibited because compaction or other factors have reduced the number of macropores. Additional research is needed on the biogeochemistry of fractures and its effect on nutrient transport within glacially derived soils.

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